LIGHTNING PROTECTION
OF BURIED CABLE
BY SEMI-CONDUCTING JACKETS

BY

H. D. CAMPBELL

Northern Electric
COMPANY LIMITED

MONTREAL, CANADA

Prepared for Presentation
at the

FOURTEENTH ANNUAL SYMPOSIUM
ON
TECHNICAL PROGRESS IN COMMUNICATIONS WIRES AND CABLES

at
Atlantic City, New Jersey
December 2, 1965

ERRATA

Page 15, FIG. III

| 2.0/22.0 WAVE | *should read* | 2.0/12.2 WAVE |
| 2.0/12.2 WAVE | *should read* | 2.0/22.0 WAVE |

Page 19, FIG. XI

2. Water Immersion at 75°C for 15 days

should read

2. Water Immersion at 75°C for 15 weeks

LIGHTNING PROTECTION OF BURIED CABLE
BY SEMI-CONDUCTING JACKETS

by
H. D. Campbell
Northern Electric Co. Ltd., Montreal

SUMMARY

Semi-conducting jackets on buried telephone cable will be subjected to heavy surge currents caused by local lightning strokes to ground. The impulse current strength of a semi-conducting polyethylene compound, having a nominal resistivity of 20 ohm-cm, is measured and the effects of some environmental factors assessed. It is concluded that the probability of surge current rupture of the cable jacket in service is very small except when direct strokes to the cable occur.

INTRODUCTION

For the past 20 years polyethylene has been used as an overall jacket for telephone cables. Typical constructions are the Alpeth and Stalpeth sheaths in which the overall polyethylene jacket is applied over aluminum or aluminum and steel tapes.

With the recent trend to buried plant these sheath constructions have presented a problem not experienced by the lead sheath construction they replaced. When cable is buried in rural areas, the polyethylene jacket is susceptible to damage from local lightning strokes to ground. The most objectionable feature of this type of damage is multiple punctures of the jacket that may occur for hundreds of feet along the cable, permitting the ingress of water and eventual degradation and/or disruption of service.

Different methods of approach are being used to reduce these failures caused by the high voltage between the cable shield and surrounding earth. An additional jacket placed underneath the cable shield is often used. This jacket will remain intact preventing water from entering the cable even if the outer jacket is punctured. Another method is the provision of shield wires situated a few inches above the cable that provides a low impedance path for the lightning current. A third method, which has received a great deal of attention, is the use of a semi-conducting jacket in place of the conventional polyethylene jacket. If the semi-conducting jacket can withstand high current densities without rupture while still providing the same degree of corrosion and moisture protection at the same cost as the conventional polyethylene jacket, it would appear to be the logical solution to the problem. This paper deals with one of the requirements of the semi-conducting jacket — its ability to withstand high surge currents. The laboratory results are applied to field conditions in an attempt to predict service performance.

GENERAL

When lightning strikes near a buried telephone cable, a portion of the surge current flowing in the surrounding earth will flow to the cable and be conducted along the shield that forms a low impedance path. If the shield is covered with a conventional insulating

jacket, i.e., polyethylene, a voltage will be impressed on the jacket and, if the stroke is severe, the jacket will rupture. On the other hand, if the jacket is semi-conducting, the surge current will flow through the jacket and again, if the current density is very high, the jacket may rupture because of the high energy loss in the material.

It is apparent then that to determine if semi-conducting material will withstand stroke currents, the surge current density required to rupture the material must be measured, just as impulse (voltage) strengths of insulating materials must be measured, to determine if they will withstand surge voltages that may be impressed upon them in service.

Having determined the impulse current strength of the material, it is necessary to apply the information to field conditions where the energies involved are much larger than can be generated in the laboratory and where the surge currents may take on a great variety of waveshapes and magnitudes depending upon the type and severity of the lightning stroke, the earth resistivity, the relative location of the cable and other factors. The literature contains sufficient data to compute the approximate values of surge current densities and their waveshapes that must be transmitted by the semi-conducting jacket under given conditions. We, therefore, believe it is practical to apply the laboratory data to field conditions and predict within reasonable approximation the behaviour of the jacket when subjected to lightning strokes.

A number of different semi-conducting compounds formulated for cable jackets have been developed for commercial use. The important electrical parameters of these materials are their resistivities and surge current strengths just as resistivity and impulse strength are important parameters of an insulating material. For high surge current strength it is fundamental that the resistivity be kept to a low value. In addition, for the material to be of practical use the resistivity should remain reasonably constant with time, temperature, bending and other conditions of environment to which the cable may be subjected. It was necessary to measure the effect of these and other factors on the impulse current strength and to a somewhat lesser extent the effects on resistivity because it was expected that changes in resistivity would be reflected in corresponding changes in impulse current strength. Initially several different materials were investigated but most of the more important work was carried out on one material that is now commercially available.

SURGE CURRENT GENERATOR

Since our laboratory does not include an impulse current generator, the existing high voltage impulse generator circuit was modified and used as an impulse current generator. In this configuration all capacitors are arranged to fire in parallel. This method causes some distortion of the wave tail when a plurality of stages are used because of the different impedance of each parallel stage. A maximum of four stages were used to keep the distortion to reasonable limits. In this configuration the maximum stored energy was 40 kilowatt-seconds, the peak current about 15 kilo-amperes, and the waveshape 2.0/22 microseconds, i.e. the time to crest value was 2.0 microseconds and the time to half value 22 microseconds.

The impulse current was measured by a conventional tubular surge current shunt. The voltage developed across the shunt was fed by voltage terminals and leads inside the tube through a coaxial cable to a cathode ray oscillograph and an impulse peak voltmeter. Since the resistance of the test samples formed only a very small fraction of the total resistance of the impulse current circuit, the waveshape remained virtually constant for all samples. The waveshape was changed, when required, by varying the number of stages. The peak current of each impulse was monitored by the impulse peak voltmeter but only periodic use of the cathode ray oscillograph was required. A schematic view of the test circuit is shown in Fig. 1.

2

RESISTIVITY TESTS

Initial Work

All the initial work both for impulse current strength and resistivity was done on moulded slabs and included a number of different compounds. The resistivity measurements on these slabs were made in a longitudinal direction in accordance with ASTM Standard D 991-60.

The longitudinal resistivity was measured in preference to the resistivity in the perpendicular plane because of the difficulty of eliminating contact resistance in the latter method. It was felt that the slabs would not exhibit appreciable anisotropic effects. In work on cable jackets to be described later the radial resistivity was measured.

Since general improvement in impulse current strength was found at the lower resistivities, this work indicated the more promising compounds for further investigation.

Further Work

All further resistivity tests were made on a semi-conducting polyethylene compound which was commercially available and with which our Company has had some extrusion experience. It had a nominal resistivity as stated by the manufacturer of 20 ohm-cm. For our test purposes this compound was applied to two different cables: (1) directly over a 700 MCM copper strand to a nominal thickness of 130 mils and (2) as a jacket on an Alpeth-sheathed telephone cable to a nominal thickness of 80 mils and a nominal overall diameter of 1.16 inches.

Resistivity measurements were made both in the radial and the longitudinal directions. The method of longitudinal measurement has been described. For the radial measurements the sample was removed from the cable, coated with silver paint (Du Pont 4922) on both the outer and inner surfaces for an axial length of 2 inches and then replaced on the cable. The outer conductive surface was reinforced with a wrapping of tin foil tape. The paint was allowed to dry for at least 24 hours before the measurements were taken. A dc voltage was impressed across the sample so that the maximum current was 190 milliamperes to prevent internal heating. The voltage was measured by an electrometer. To determine if the boundary or contact resistance was causing appreciable errors the following procedure was adopted. A small hole about 0.1 inch in diameter was left in the silver paint coating and the area of the hole carefully prodded with a needle-sharp probe. It was found that the voltage dropped appreciably as the probe was moved toward the centre of the hole but, when the probe was moved to within very small distances from the edge of the silver paint, the voltage was nearly the same as that obtained on the painted surface. It was concluded that the boundary resistance was small.

Measurements were made at elevated temperatures on samples placed in a hot air oven. Initially measurements in the radial direction were attempted but, because very high values were obtained, it was thought that the contact resistance might be changing. Due to the practical difficulty of using the probe inside the oven it was decided to measure the variation in longitudinal resistivity with temperature and assume the variation would be similar in the radial direction. Some measurements were made after the material was annealed at 100 C for 48 hours and allowed to cool to room temperature. For all elevated temperature measurements the impressed voltage was kept constant to eliminate any error due to internal heating as the resistance increased. Measurements were also made on samples which had been immersed in a hot water bath at 75°C for 15 weeks.

3

The results of the resistivity measurements are given in the following tables.

RESISTIVITY (OHM-CM) AT 25°C

	COPPER-STRAND JACKET		ALPETH JACKET	
	Virgin	After Annealing	Virgin	After Water Immersion
Radial	200	70	50	90
Longitudinal	200	110	50	100

RESISTIVITY VS TEMPERATURE – COPPER-STRAND JACKET

Temperature °C	25	30	40	50	60
Longitudinal Resistivity (ohm-cm)	200	220	390	910	2700

The copper-strand jacket exhibited higher resistivities than the Alpeth jacket, probably due to different extrusion conditions[1]. The values obtained for the virgin jackets are believed to be representative of the material under normal extrusion conditions. A significant increase in resistivity occurred after water immersion.

It will be shown later how the resistivity values and changes in values affect the impulse current strength.

IMPULSE CURRENT MEASUREMENTS

General

Since the impulse current waveshapes that could in practice be produced by the impulse generator were of much shorter duration than those that occur in the field, it was necessary to determine what effect the waveshape had on the impulse current strength of the material. In the measurements two different waveshapes were used by using two and four stages of the generator. In addition, some tests were made with one generator stage. The other variables investigated were: temperature, bending, repeated impulses, water immersion, thickness, series insulation, air gap and polarity. All the samples were taken from the two cables already described, the majority from the 700 MCM copper strand. All tests except those for polarity were made with negative polarity.

Definitions

For the purpose of this paper three definitions are stated.

Impulse current strength: the maximum peak current the material can withstand without rupture when subjected to two consecutive impulses of stated waveshape.

The use of two impulses without failure was considered necessary to eliminate the possibility of a partial failure or some degradation of the material occurring on the first impulse. Such damage could not be detected by the normal methods of observation.

Rupture strength: the minimum peak current required to rupture the material when subjected to one impulse of stated waveshape.

4

The rupture strength was used as a basis for most of the tests because it is valid for comparative tests and is much simpler than the application of repeated impulses.

Rupture: a hole in the material that can be seen with the naked eye.

The definition of rupture is required because visual observation was the only reliable way of detecting the rupture. In this respect these tests were far different from conventional impulse voltage tests in which there is an unmistakable change in the waveshape when rupture occurs. In the impulse current tests on these materials there was no detectable change in the waveshape when failure occurred and often no detectable change in peak current.

Preparation of Test Samples

Samples about five feet long were cut from the cable and electrodes placed as shown in Fig. II. The lengths of the electrodes were kept as long as possible to keep edge errors small, and in most cases three-inch electrodes were used. Some two- and four-inch electrodes were also used.

Electrode Edge Effects

The initial work on impulse current strength was conducted on moulded slabs. In this work the slab was inserted between two flat brass electrodes one inch in diameter. The current surge produced a substantial spark discharge around the periphery of the electrodes. This discharge was probably forced radially outwards by the sudden expansion of the ionized air. It was obvious that this fringing effect increased the electrode area and that the error so introduced could be quite large. In addition, this error was considered to be greater on samples having higher resistivities since the voltage initiating the spark discharge would be greater. It may then be stated that the higher the sample resistance the greater the effective electrode area. For this reason, impulse current strength comparisons of slabs of different thicknesses and resistivities lead to erroneous results.

Initial work on cable jacket samples gave unmistakable evidence that edge effects were also causing large errors. Spark discharges were observed from the ends of the electrodes and large changes in electrode area did not cause proportional changes in the rupture strength. In fact, in one case it was impossible to rupture the material even when the electrode length was successively reduced from two inches to less than 0.1 inch. When insulating tape was applied to suppress the spark discharge as shown in Fig. II, rupture was readily obtained on a four-inch electrode. Further tests with guarded electrodes and with different sizes of electrodes showed that the electrode arrangement in Fig. II produced quite small edge errors, and increased the effective length of the electrode by not more than 0.2 inches.

Detection of Rupture

The electrode was examined visually after each impulse to determine if rupture had occurred. Rupture was exhibited by a hole in the tin foil and in the covering insulating tape. In a few cases where the energy necessary for rupture was small, only small bulges were noted. Very careful checks were made to ensure that rupture did not occur without visual effects on the outer electrode. In the doubtful cases the electrode was dismantled. Most of the ruptures occurred at the edge of the electrode or under the wire connecting the electrode to the generator lead. The slight indentation under the wire fastener is believed to have weakened the material slightly. The failure at the edge of the electrode

5

is believed to have been caused by current concentrations analogous to that experienced in voltage tests on such configurations. Since failures did occur at other areas of the electrode, it is believed that the current flow was substantially uniform over the entire electrode area.

Samples

Rupture strength measurements were made both on the Alpeth jacket and the copper-strand jacket. It was found that the rupture strength of the Alpeth jacket was substantially higher than that of the copper-strand jacket. This increase in strength is to be expected from the lower resistivity values of the Alpeth jacket. Comparison of the Alpeth jacket and the copper-strand jacket is shown in Fig. III.

The effect of waveshape was investigated on both jackets. On the copper-strand jacket, the effect of thickness, temperature, bending, repeated impulses, air gap and positive polarity was investigated. On the Alpeth jacket, the effect of water immersion and series insulation was measured. Over 300 specimens (electrode configurations) were tested in the investigation.

The individual specimens were tested in groups of six. After some initial experience the rupture value could be approximately predicted. The impulse current was changed by about five percent for each individual specimen resulting in failure in some and no failure in the others. The rupture values were found to be reproducible over a range of about ten percent. Typical ruptures are shown in Fig. IV.

The Effect of Waveshape

The general effect of waveshape is shown in Fig. V but a more accurate comparison was made between the 2.0/12.2 microsecond wave and the 2.0/22.0 wave for which average values were obtained from about 50 specimens. The energy function under each wave was measured and compared. Due to some distortion the decay time to half value could not be accurately measured in the usual manner. The equivalent energy function and waveshape were measured by plotting the i^2t curve and measuring the area under the curve. The energy functions for the two waveshapes, measured in this manner, are shown in Fig. VI. It can be seen that the energy required for rupture is virtually equal for both.

The energy content of an impulse wave is given [2] by the expression:

$$\text{Energy (E)} = \frac{I^2 d}{1.38}$$

where I = peak current
       d = exponential decay time to half value.

(Note that d equals the time to half value minus the time to peak value).

When d is small as in the waveshapes investigated, a more accurate expression is:

$$E = I^2 \left(\frac{t_o}{3} + \frac{d}{1.38} \right)$$

where t_o = the time to peak value.

From the latter expression, the waveshape values are derived and have the same energy content as the slightly distorted waveshapes generated in the measurements.

6

Repeated Impulses

Initial work showed that repeated impulses greatly reduced the required rupture current. Trials were conducted with impulses at 30-second and at 90-second intervals. Although the temperature rise of the samples appeared to be small in both cases, there was a small but definite change in results. Further experiments with a 15-minute interval between impulses resulted in far higher rupture values. Values of the one-shot rupture (i.e., rupture strength) are compared in Fig. V to rupture values obtained with at least three repeated impulses (i.e., impulse current strength). These results show that the repeated impulses cause a fairly small reduction of the required rupture current.

Temperature

The rapid increase of resistivity with increase in temperature indicated that the impulse current strength would also be dependent upon the temperature. Tests were carried out in a heating chamber as shown in Fig. VII. One test was made below ambient temperature. The samples were subjected to the test temperature for at least one hour before the tests were begun. Rupture strength versus temperature is plotted in Fig. VIII. The curve of rupture current versus temperature is a straight line and indicates that at about 80°C the rupture current would be negligible compared to that at room temperature.

Thickness

Tests were made on three different thicknesses of jacket. The samples were removed from the cable and placed on a mandrel. Two sets of samples were turned down on a lathe to a thickness of 105 mils and 50 mils. The third set was not reduced in thickness but was tested on the mandrel to ensure uniform conditions for the three sets of tests. The results are shown in Fig. IX. The value obtained for the 50-mil thickness is slightly less than values obtained for full thickness in this and other tests. This reduction is believed to be due to the non-uniform current flow in the thin samples in which the strand wire convolutions are an appreciable fraction of the total thickness. It can be said that rupture strength is independent of thickness and this result is to be expected if the rupture strength is a function of energy.

Bend Tests

Published data[3] has shown how resistivity increases when semi-conducting material is subjected to a tensile force and elongated. It follows that the impulse current strength of the jacket is likely to be reduced when the cable is in a bent position. Tests were conducted with two different size mandrels on which the cable was subjected to four 180-degree reverse bends and held in the bent condition during the tests. The results are shown in Fig. X and indicate a small reduction in impulse current strength can be expected at bends encountered in service. The reduction in strength may be less on a telephone cable in which the core is softer than the copper strand of the sample used in the tests.

Water Immersion

A series of tests was performed on a sample that had been immersed in a 75°C water bath for 15 weeks. It was felt that this was a practical test to simulate a cable in a wet environment and to accelerate any effects that such an environment would cause. It is known that the material, being heavily loaded with carbon black, has a relatively high water absorption compared with conventional polyethylene jackets and it was judged that the time interval was sufficient for essentially maximum absorption to be obtained.

7

The effect on rupture strength is shown in Fig. XI. The substantial decrease is expected from the resistivity measurement. It is believed that the decrease in rupture strength was the effect of water absorption rather than aging, and that no significant change would occur with continued immersion.

Air Gap

It is recognized that under field conditions there will be no conductor in intimate contact with the cable and that soil ionization may occur in the vicinity of the cable. To simulate these conditions to some degree a 30-mil air gap was introduced between the electrode and cable jacket. In other respects no changes were made in the electrode arrangement. No reduction in rupture strength was found to occur, rather an increase was obtained. Previous work on moulded slabs indicated no change in rupture strength when a similar air gap was introduced.

Series Insulation

In some cable constructions it is the practice to apply a flooding compound between the metallic envelope or cable shield and the covering jacket. This compound inhibits the flow of moisture along the cable shield in the event of localized damage to the jacket. It appeared obvious that the introduction of such compound underneath a semi-conducting jacket would prevent uniform flow of current through the material thereby reducing the impulse current strength. Initial tests on moulded slabs in which a 5-mil insulating paper was inserted in series with the compound gave marked reduction in rupture values, indicating that the use of any insulating material in this manner would cause prohibitive deterioration of impulse current strength. It was not considered necessary to carry out tests with flooding compound.

To facilitate the fabrication and forming of a conventional corrugated shield around the telephone cable core a thin film of oil may be applied. Some tests were performed with a thin film of this oil between the outer electrode and jacket. No serious deterioration was observed but it is recognized that the tests were only of a very general nature. It is possible that further deterioration could occur with absorption of the oil in the material. It should be noted that the Alpeth jacket tested did not have a film of oil over the corrugated shield.

Positive Polarity

A few tests were made to determine if positive polarity would yield different results than negative polarity. The results indicated about 20% reduction in rupture strength. The significance of this and other reductions in rupture strength will be discussed later.

Rupture Strength and Resistivity

It was found that resistivity under impulse currents was smaller than the measured values. Specimens whose measured resistance represented a substantial fraction of the series resistance of the generator circuit produced very small effects on the peak currents. Only small heating effects were observed. The experimental data show that the mechanism of rupture is dependent upon the energy dissipated in the material. The dissipated energy, however, appears to be a function of an effective resistivity that is lower than the measured values. Although the measured resistivity is indicative of the rupture strength, no precise relationship has been found.

8

FIELD CONDITIONS

The surge current densities to which the semi-conducting jacket will be subjected in the field will depend upon the severity of the lightning stroke, the proximity of the stroke, the soil resistivity and other factors. From published data[4] it is possible to define these factors within reasonable limits.

Lightning Strokes

The peak current of lightning strokes is on the average about 30,000 amperes, while about 95% of the peak currents are less than 100,000 amperes. It is known, however, that a lightning discharge often consists of several strokes with a relatively low current flowing between them for an interval of about 1/10 second. Discharges of more than six strokes are quite rare. Measurements of waveshapes indicate that the current usually reaches its crest value in 5 to 10 microseconds and decays to half value in 25 to 100 microseconds. The polarity of the stroke is usually negative. From these data it is evident that a discharge consisting of three strokes, each having a waveshape of 5/65 microseconds and a peak current of 100,000 amperes would be representative of an un-usually severe discharge. This discharge will be used as a maximum value for computing the dissipated energy in the cable jacket.

Current Flowing to Cable

When a lightning stroke enters the ground, the current spreads and, if there is a cable near the stroke point, the stroke may arc to the cable. Even if no arcing occurs, much of the current may still flow to the cable sheath because of its low impedance to remote ground. If no cable is in the vicinity of the stroke point and the resistivity of the soil is uniform, the current will flow radially in a hemisphere as represented in Fig. XII.

The stress in the earth at radius r is given by the expression:

$$e = \frac{I\rho}{2\pi r^2}$$

where I = peak current

ρ = soil resistivity in meter-ohms

r = meters

e = volts per meter.

If e_o is the breakdown gradient of the soil, then the soil will be ionized for a distance r_o where

$$r_o = (I\rho/2\pi e_o)^{1/2}$$

r_o may be considered to be the radius of a conducting hemisphere of negligible resist-ivity.

The resistance encountered by the lightning channel is given by:

$$R_o = \frac{\rho}{2\pi r_o}$$

9

If a buried cable is near the stroke point, the approximate distance the stroke may arc is given by Sunde[4]:

$$r_a = 0.047 \; (I\rho)^{\frac{1}{2}} \text{ meters when } \rho \geq 1,000 \text{ meter-ohms}$$
$$\text{and } r_a = 0.08 \; (I\rho)^{\frac{1}{2}} \text{ meters when } \rho \leq 100 \text{ meter-ohms}$$

where I is expressed in kiloamperes, and e_0 is 500,000 volts per meter and 250,000 volts per meter for resistivities of 1,000 meter-ohms and 100 meter-ohms respectively.

If ρ is 1,000 meter-ohms, representative of high resistivity soil, and I is 100,000 amperes then:

$$r_0 = 5.6 \text{ meters}$$
$$R_0 = 28.2 \text{ ohms}$$
$$r_a = 14.8 \text{ meters}$$

The potential E at the stroke point with reference to remote ground is:

$$E = IR_0 = 2820 \text{ KV}$$

When a cable is present just beyond the arcing radius the summetry of Fig. XII will be disturbed. A rigorous solution of the division of current between remote earth and the cable is beyond the scope of this paper; a satisfactory approximation, however, can be made by using certain simplifying assumptions. First, the potential of the cable will be considered to be the same as remote ground. Secondly, although a greater portion of current will flow in the direction of the cable with attendant greater soil ionization on the cable side of the stroke point, the conducting sphere cannot be expected to be appreciably distorted because current will flow from a large part of the surface area to an object "connected to it" by a path having relatively high resistance compared to that to remote ground. The resistance between the conducting sphere and the cable will be at a minimum opposite the stroke point. The stress in this area will be at a maximum. If the sphere, which is large compared to the cable, is considered to be "seen" by the cable opposite the stroke point as a plane surface, the stress at the cable can be estimated and the soil around the cable will be ionized for an approximate distance:

$$r_{oc} = \frac{E}{e_0 \ln \frac{2S}{r}}$$

where S is the distance between the cable and sphere, taken as 10 meters, and r is the radius of the cable.

Using values already obtained and assuming a cable radius of one inch (0.025 meters):

$$r_{oc} = 0.85 \text{ meters}$$

If we now consider one meter of cable opposite the stroke point just beyond the arcing radius, the current entering the sheath will be approximately uniform. The resistance between the conducting sphere and a conductor of effective radius of 0.85 meters can be approximated by analog methods of plotting to scale cross-sections on semi-conducting paper. The resistance measured by this method was found to be about 1100 ohms. The current entering one meter of sheath is then:

$$I = \frac{2.82 \times 10^6}{1100} = 2560 \text{ amperes}$$

10

Low Resistivity Soil

The values just given are for high resistivity soil. Similar calculations using a resist-ivity of 100 meter-ohms, representative of low resistivity soil, give the following values.

$$r_o = 2.52 \text{ meters} \qquad R_o = 6.32 \text{ ohms}$$
$$r_a = 8.0 \text{ meters} \qquad E = 632 \text{ KV}$$
$$I = 5700 \text{ amperes per meter}$$

In both cases it was assumed that the cable was just beyond the arcing distance. This distance is much shorter in low resistivity soil. A higher value of current flow to the cable can, therefore, be expected under the assumed conditions. The values of current flow are, of course, general approximations but much more rigorous and detailed solutions have indicated the values to be very conservative. It is evident that strokes arcing to the cable will cause failures because the measured rupture current is lower than virtually all lightning strokes.

Experimental Data and Field Conditions

It is necessary to apply the measured laboratory data to field conditions. The object is to show that, unless the cable is subjected to a direct stroke or a stroke arcing to the cable, the probability of jacket rupture is very small.

Impulse Current Strength

It has been shown that a number of factors affect the rupture strength of the semi-conducting material. It is, therefore, necessary to determine a value that will be repre-sentative for practical field conditions. In order to obtain this value certain assumptions must be made.

Resistivity – Two rather different values were obtained for resistivity – 50 ohm-cm and 200 ohm-cm. It is believed that these two values represent the upper and lower ranges that will normally be obtained for extruded jackets if recommended extrusion techniques are followed. Since the rupture strength is dependent upon the resistivity, a conservative value of resistivity should be used. It is believed that 200 ohm-cm is representative of the maximum value that normally will be obtained. A resistivity of 200 ohm-cm will, therefore, be assumed.

Temperature – The soil temperature at a 3-foot depth is normally assumed to be 20°C in Canada and a maximum of 30°C in the southern United States. A soil tempera-ture of 30°C will be assumed.

Water Immersion – A decrease of about one-third in the rupture strength was found after water immersion (Fig. XI) and this factor will be assumed to be representative.

Bending – Fig. X indicates a reduction of rupture strength of about 20 percent for a rather severe bend. This reduction is likely to be less on telephone cable than on the compact core investigated and bends of this severity in service will be few. A reduction of 10 percent will be assumed.

Repeated Impulses – The reduction of rupture strength varied from about 5 to 20 percent (Fig. V). It will be assumed that the repeated impulses cause a reduction of 20 percent, that is, the impulse current strength is 20 percent less than the rupture strength.

Other Factors – A slightly lower rupture strength was indicated with positive polarity than with negative polarity but, since most strokes are negative, no allowance will be made for this factor. The effects of a film of oil and an air gap are not considered to be of sufficient significance to warrant the application of any correction factors.

Based on the above assumptions an impulse current strength can be established for field conditions and a given waveshape. From Fig. VIII the rupture strength at $30°C$ is 950 amp/in^2 for a 2.0/12.2 wave. This value must be reduced for repetitive surges (i.e., impulse current strength) and is 0.8 x 950 = 760 amp/in^2. If the correction factors for the other assumed conditions are applied, the practical value for service conditions reduces to 0.67 x 0.9 x 760 = 460 amp/in^2.

It may now be stated that the material investigated, having a nominal resistivity of 20 ohm-cm and a resistivity of about 200 ohm-cm after extrusion, when tested with a 2.0/22.2 waveshape, has an impulse current strength at $30°C$ of 760 amperes peak per square inch. When environmental factors that may be expected in service are applied, the practical value for the same waveshape is 460 amperes peak per square inch.

The impulse current strength for a typical lightning stroke will be less because of its longer wave tail. It has been shown that the impulse current strength is dependent upon the energy contained in the wave, and that energy required for failure is independent of the shape of the wave. The energy contained in the wave is, as previously stated, given by the expression:

$$W = I^2 \left(\frac{t_o}{3} + \frac{d}{1.38} \right) R \ \text{joules}$$

where R is the effective radial resistance of the jacket per square inch.

The energy for a 2.0/12.2 waveshape is:

$$W = (460)^2 \left(\frac{2}{3} + \frac{10.2}{1.38} \right) R = 1.71 \ R \ \text{joules}$$

The same energy is required for a lightning stroke of a 5/65 waveshape. The impulse current strength for a three-stroke lightning discharge can, therefore, be computed.

$$1.71 \ R = 3 \ I^2 \left(\frac{60}{1.38} \right) R$$

from which $I = 114$ amp/in^2

The impulse current strength for the material when subjected to a lightning discharge, as previously defined, is about 115 amperes per square inch.

Probability of Failure

The great majority of buried cables in rural areas are more than one-half inch in diameter. The maximum permissable current per meter of one-half inch cable is about 7100 amperes. Since this value is greater than the calculated values, believed to be very conservative, of current flow to buried cables, it is concluded that the probability of failure is very small unless arcing to the cable occurs. Since it is known that arcing to the cable is more likely to occur in high than in low resistivity soil, the probability of surge current failure from all causes is greater in high resistivity soil areas.

12

The values for current density are for a section of cable opposite the stroke point. The current density a short distance away from this section will be much less and the problem of repetitive punctures does not arise.

While it is believed that there is a substantial safety margin in these conclusions, it is evident that to maintain this margin the resistivity of the cable jacket must be kept in the range on which these conclusions are based.

It is recognized that short term laboratory tests do not necessarily assess the stability of the material for long term service conditions. In particular, it is known[3] that degradation of the material by electrolytic action can be made to occur in the laboratory. The significance of this and other phenomena is beyond the scope of this paper. Field trials by the company with which the author is associated have been in progress for over two years and data so far obtained are very encouraging.

ACKNOWLEDGEMENTS

REFERENCES

1. Lightning Protection for Underground Cables
       by Charles Lowe
       Wire and Cable Symposium, Asbury Park, N.J., 1962.

2. Lightning Surges in Paired Telephone Cable Facilities
       by D.W. Bodle and P.A. Gresh
       Bell System Technical Journal, March 1961.

3. The Electrical Characteristics of some Resistive Plastics for the
   Wire and Cable Industry
       by R.C. Mildner and P.C. Woodland
       Wire and Cable Symposium, Atlantic City, N.J., 1964.

4. Lightning Protection of Buried Toll Cables
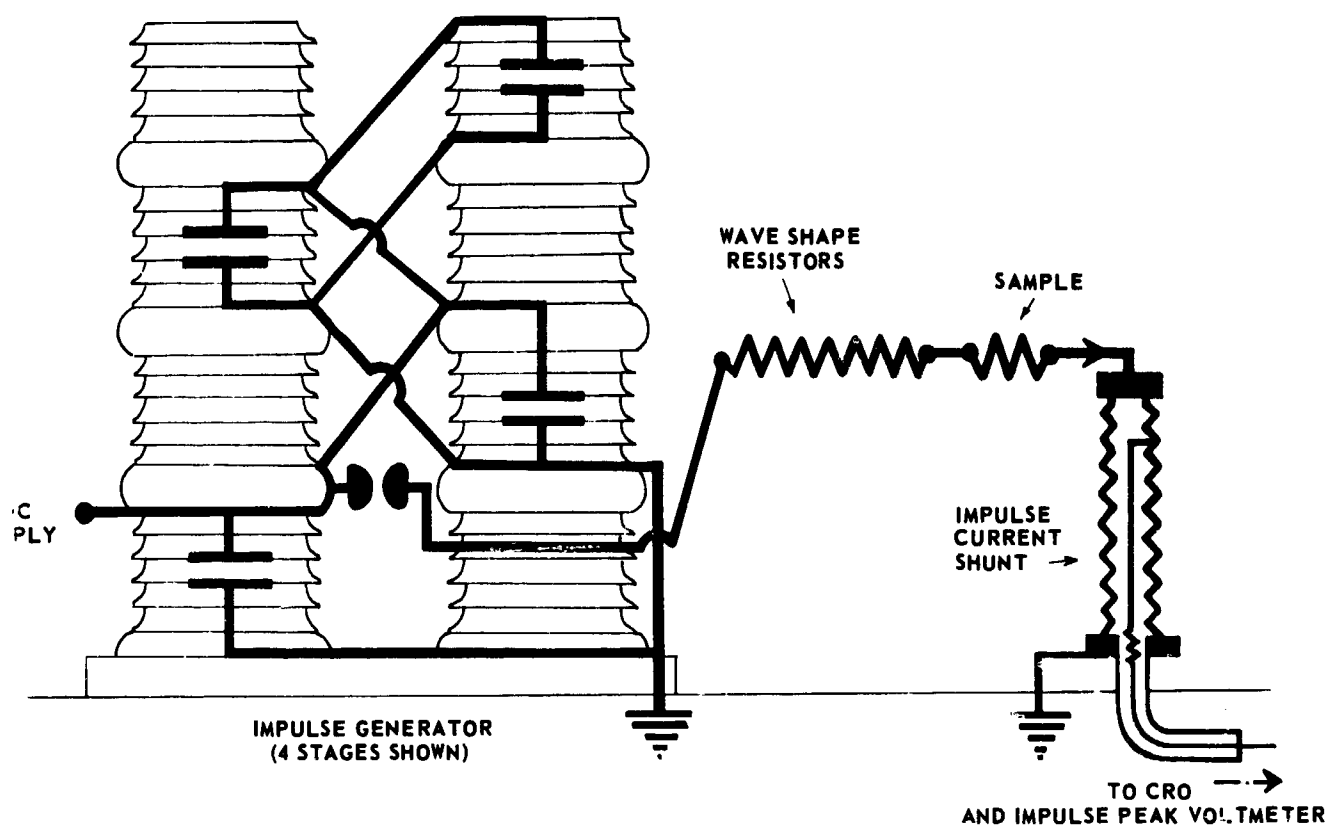   by E.D. Sunde
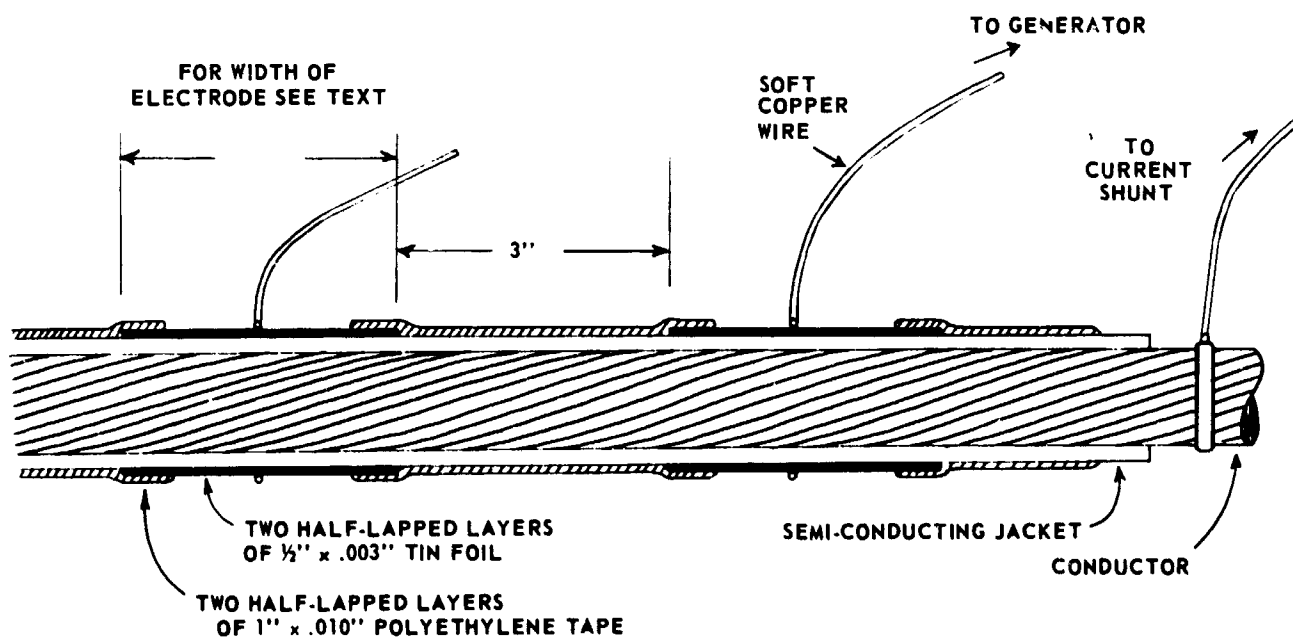   *Bell Telephone System Monograph B-1396.*

WAVE SHAPE RESISTORS

SAMPLE

'C PLY

IMPULSE CURRENT SHUNT

IMPULSE GENERATOR (4 STAGES SHOWN)

TO CRO AND IMPULSE PEAK VOLTMETER

FIG. I.   SCHEMATIC OF TEST CIRCUIT

FOR WIDTH OF ELECTRODE SEE TEXT

TO GENERATOR

SOFT COPPER WIRE

TO CURRENT SHUNT

3"

TWO HALF-LAPPED LAYERS OF ½" x .003" TIN FOIL

SEMI-CONDUCTING JACKET

CONDUCTOR

TWO HALF-LAPPED LAYERS OF 1" x .010" POLYETHYLENE TAPE

FIG. II. ARRANGEMENT OF ELECTRODES

14
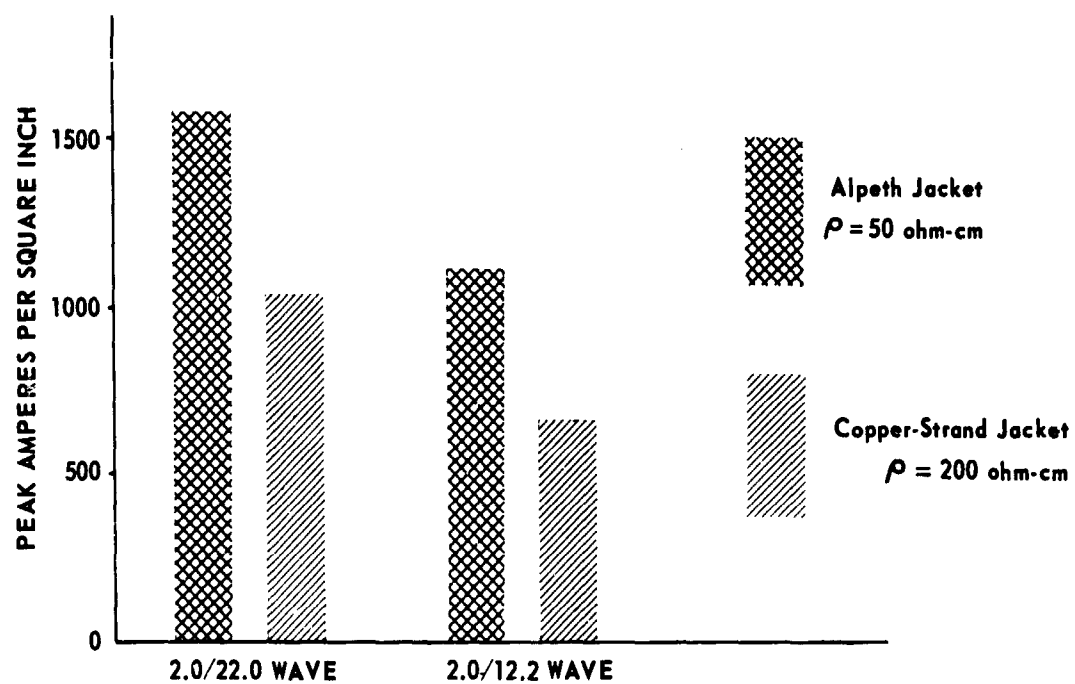
FIG. III. RUPTURE STRENGTHS OF SEMI-CONDUCTING JACKETS

COPPER STRAND   ALPETH SHEATH
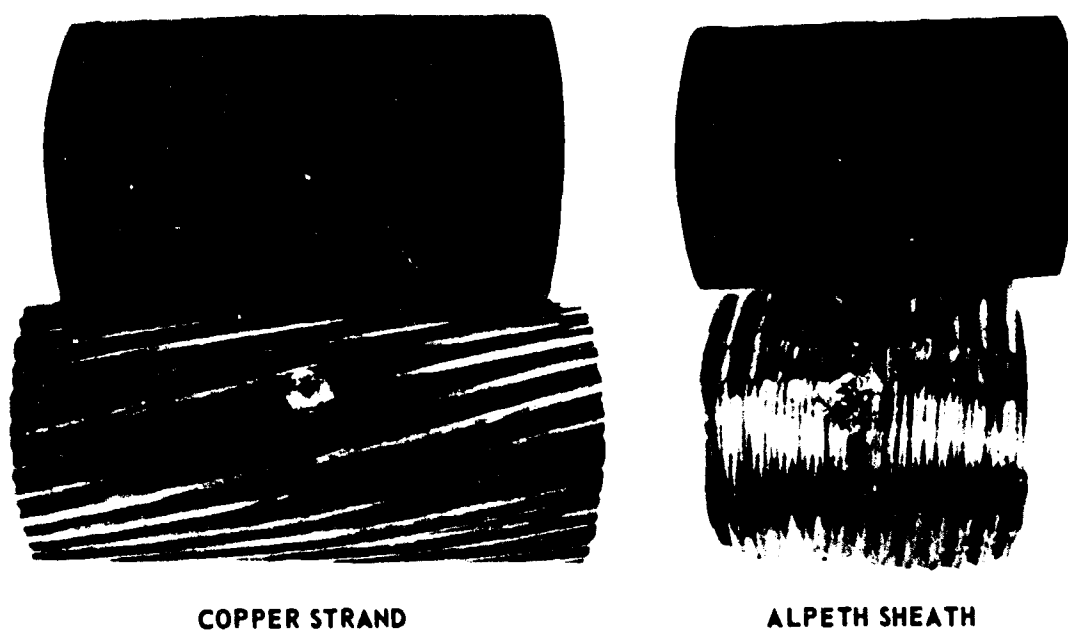
FIG. IV TYPICAL RUPTURES
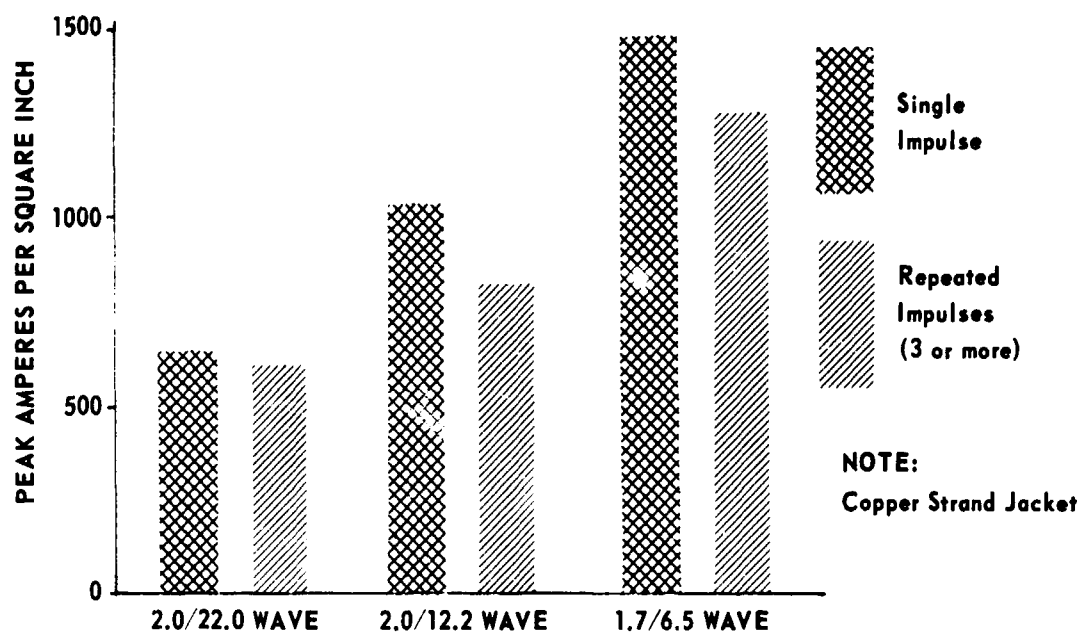
FIG. V. EFFECT OF REPEATED IMPULSES ON RUPTURE STRENGTH
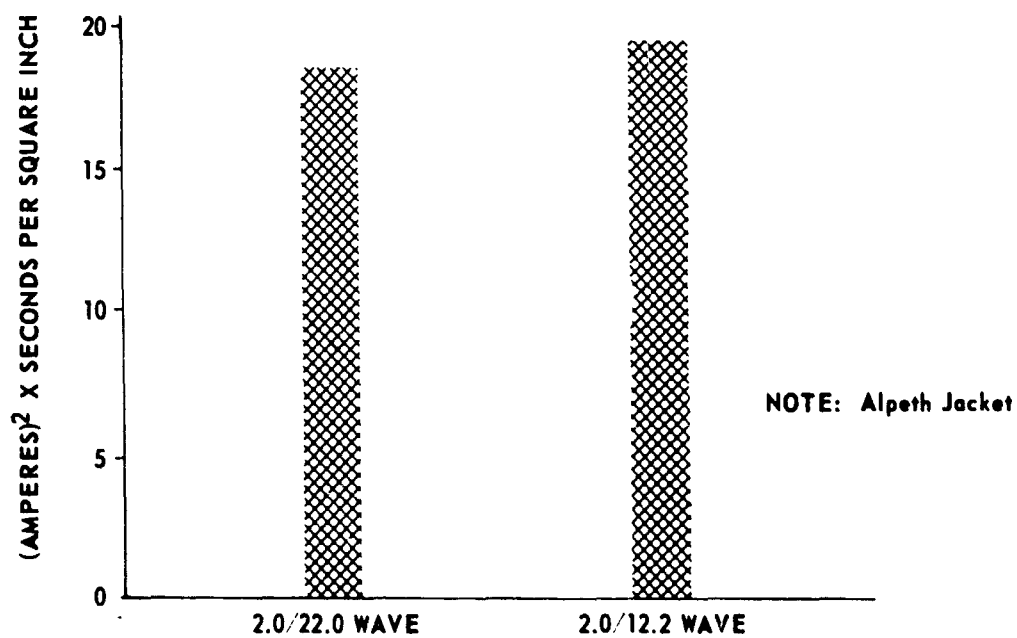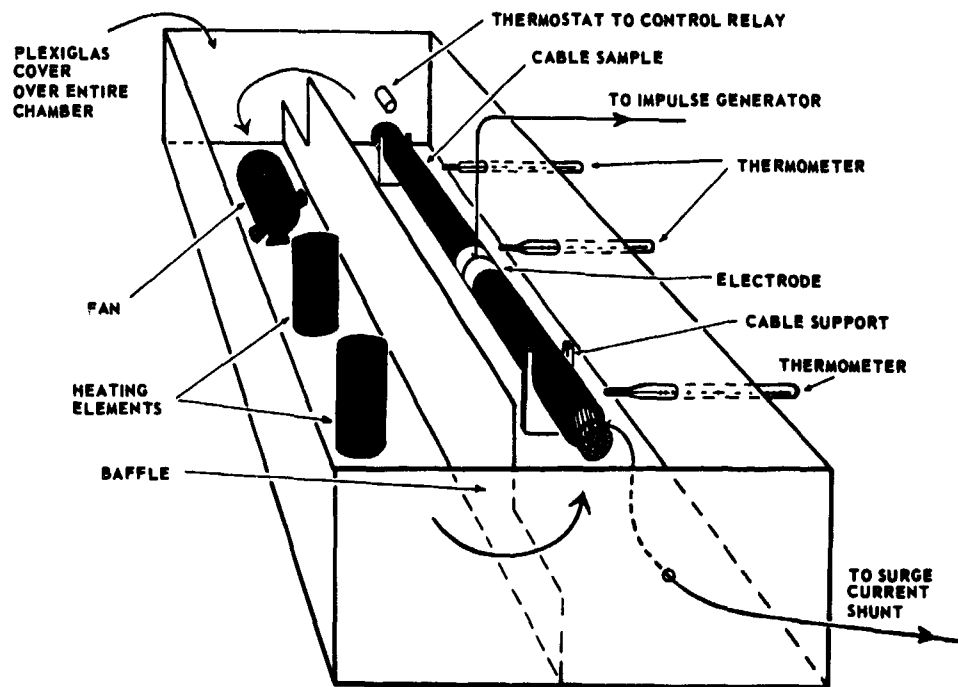

FIG. VI. EFFECT OF WAVESHAPE ON i^2t AT RUPTURE

FIG. VII.   HEATING CHAMBER

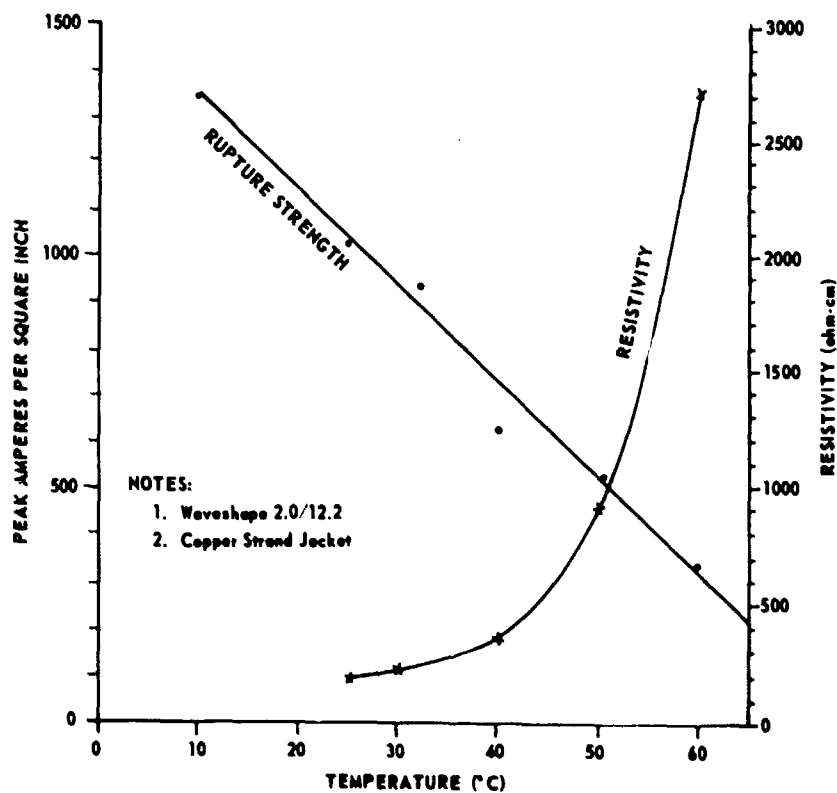

NOTES:
1. Waveshape 2.0/12.2
2. Copper Strand Jacket

FIG. VIII.   EFFECT OF TEMPERATURE ON
RUPTURE STRENGTH AND RESISTIVITY

17
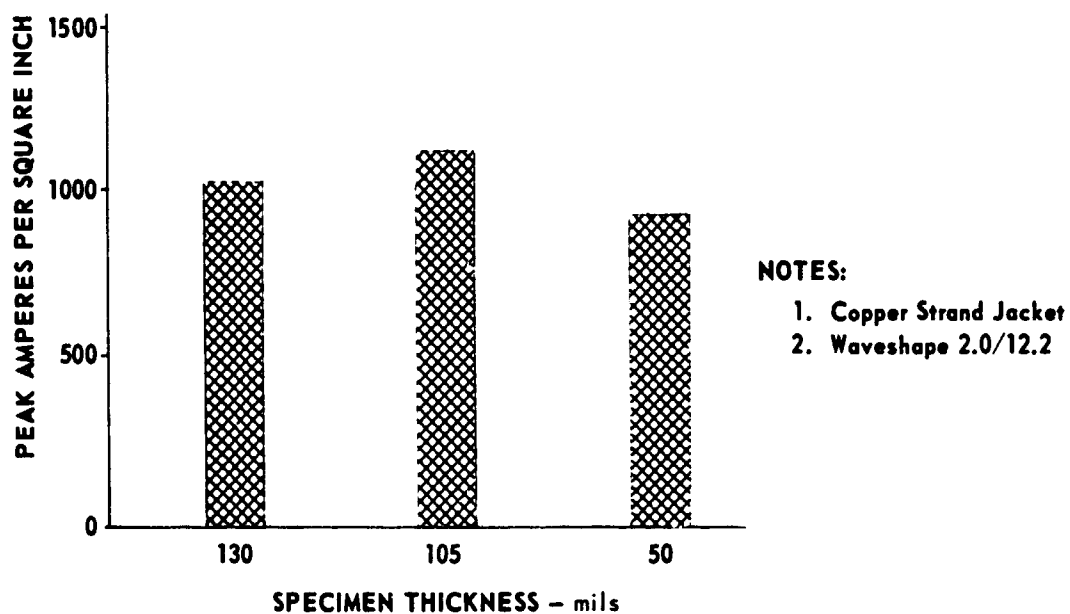
FIG. IX. EFFECT OF THICKNESS ON RUPTURE STRENGTH

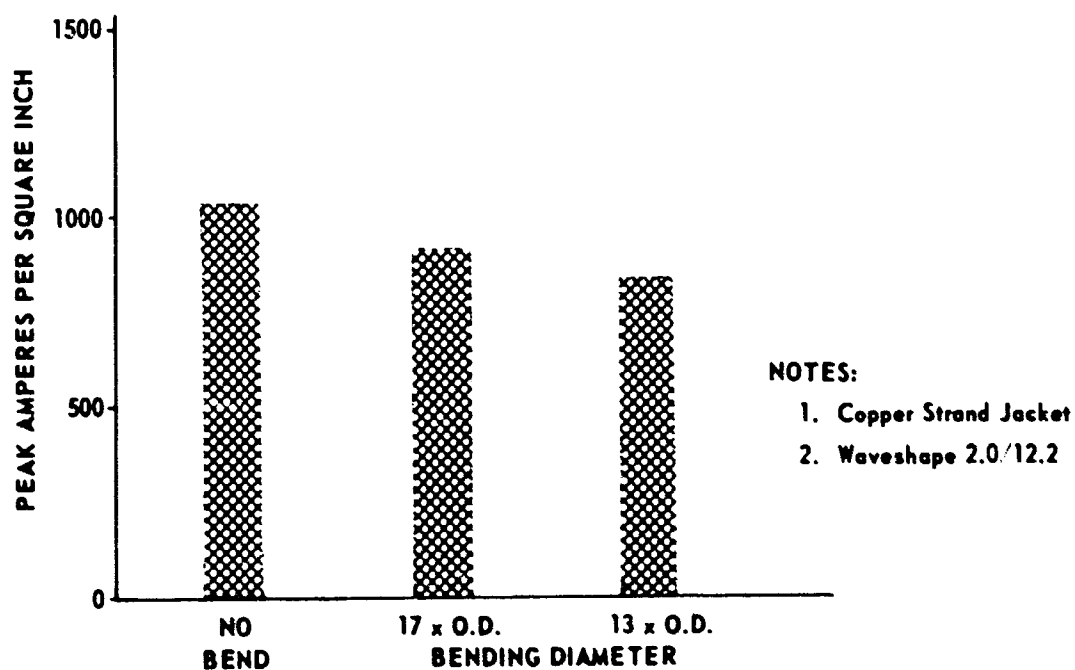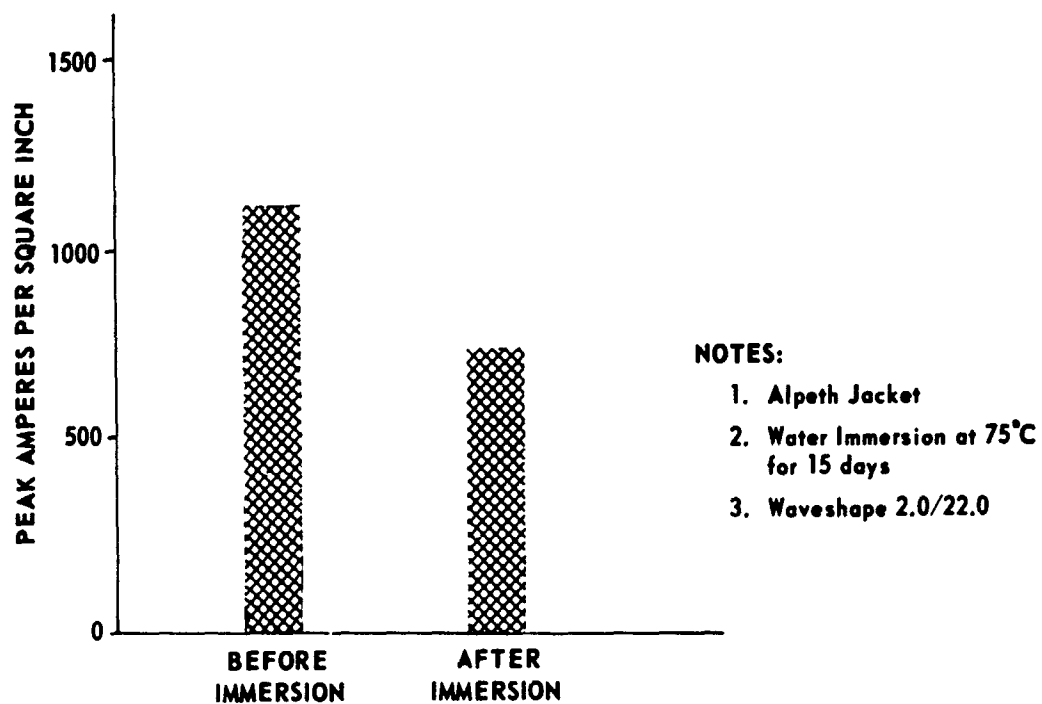FIG. X. EFFECT OF BENDING ON RUPTURE STRENGTH

18

1500

1000

PEAK AMPERES PER SQUARE INCH

500

0

BEFORE
IMMERSION

AFTER
IMMERSION

NOTES:

1. Alpeth Jacket

2. Water Immersion at 75°C
   for 15 days

3. Waveshape 2.0/22.0

FIG. XI. EFFECT OF WATER IMMERSION ON RUPTURE STRENGTH

STROKE POINT

r_a

r_o

GROUND SURFACE

CABLE

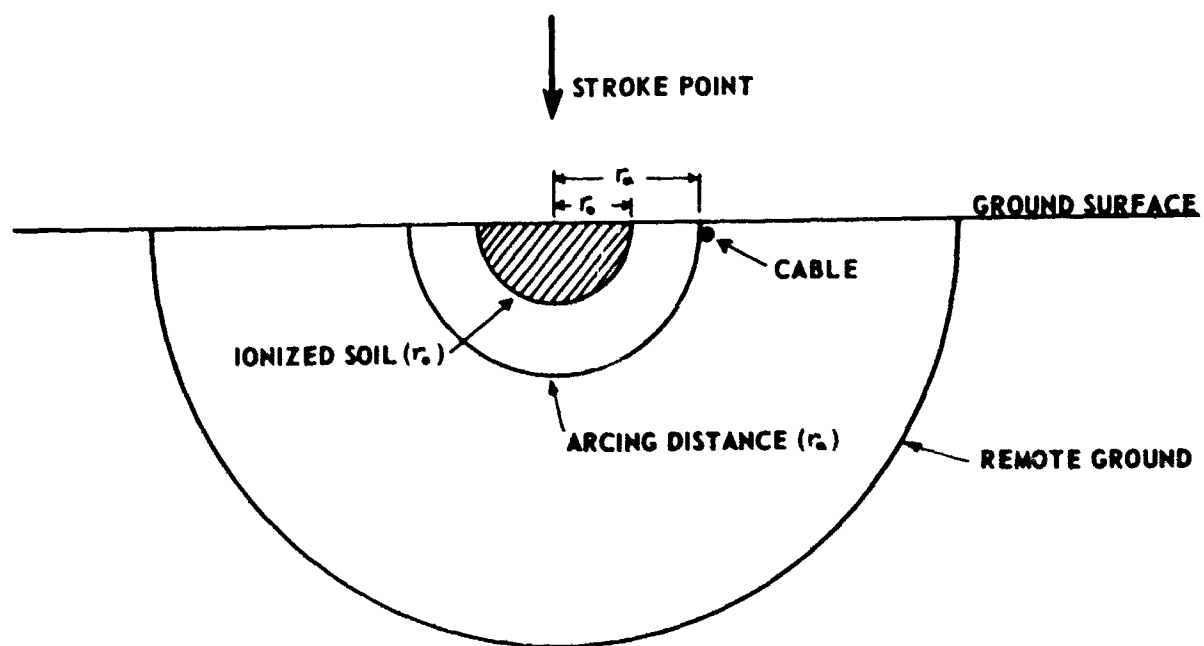IONIZED SOIL (r_o)

ARCING DISTANCE (r_a)

REMOTE GROUND

FIG. XII. EFFECT OF LIGHTNING STROKE ENTERING THE GROUND